A GNSS-Reflectometry Instrument for Wetland Extent and Dynamics

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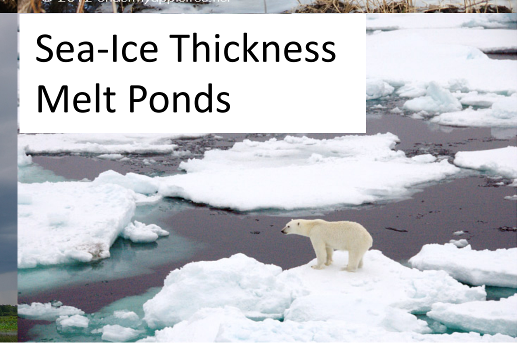
Wetland Inundation Extent


Soil Moisture

Freeze-Thaw


Heavy Precipitation


Sea-Ice Thickness
Melt Ponds

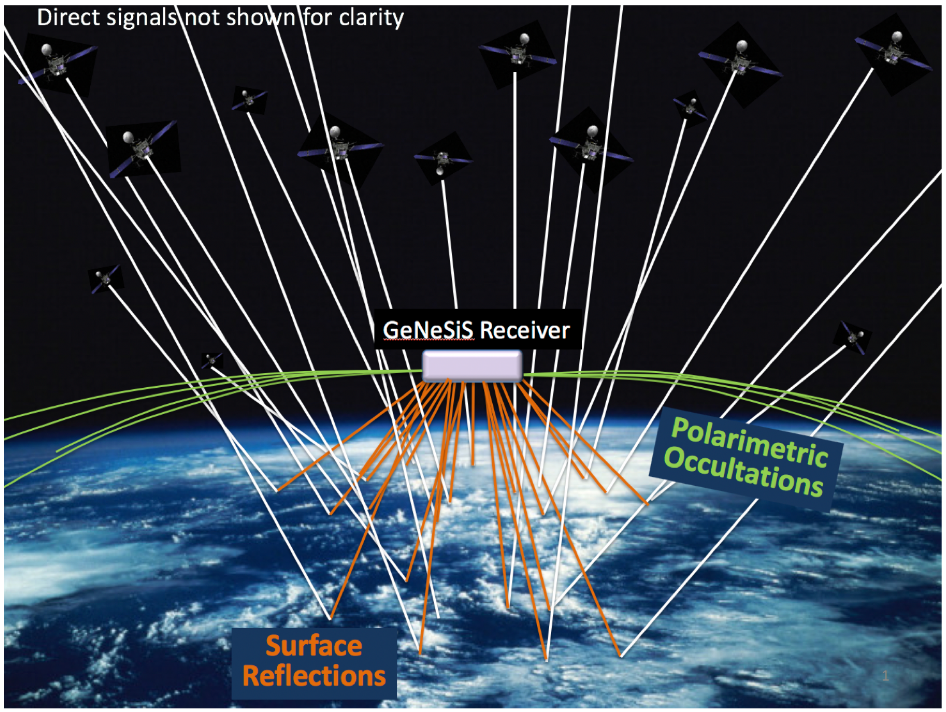
2019 Earth Science Technology Forum
June 11-13, 2019, Mountain View, CA

Outline

- Measurement concept
- Science motivation and requirements
- Instrument design

GeNeSiS

GNSS-Reflections Multistatic Radar for Wetland Dynamics



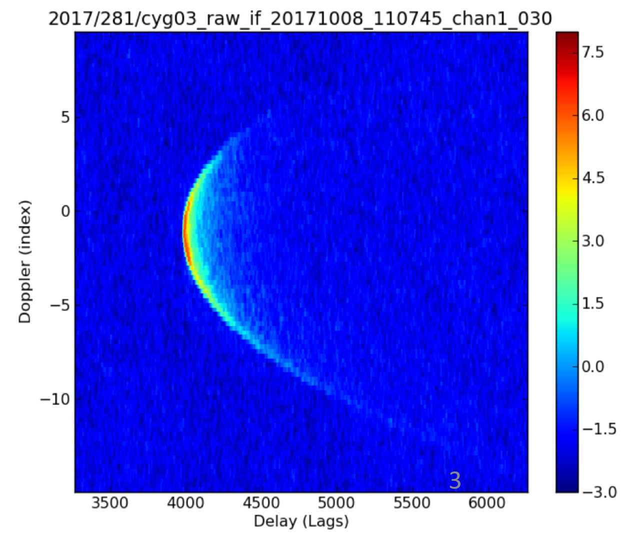
Instrument collects reflected GNSS signals (orange) for remote sensing the Earth's surface, rising/setting signals (green) for radio occultations, and direct signals (not shown) for POD. Number of links shown is typical.

Concept:
GeNeSiS collects Earth-reflected GNSS signals for remote sensing

Primary Science: Wetland inundation/extent

Primary Measurement: Delay-Doppler Map

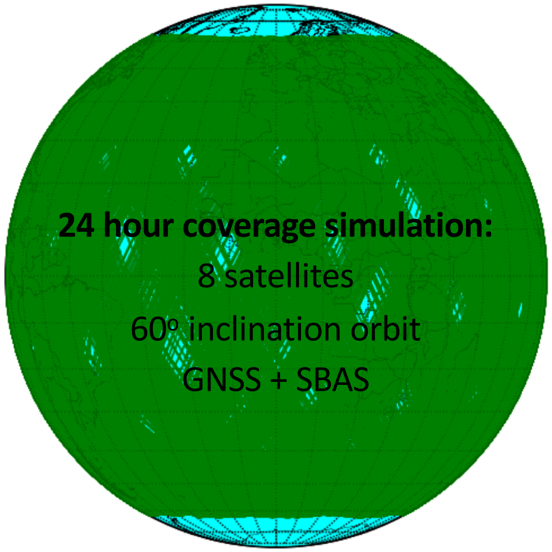
Small size/cost/power: Deploy 6-12 in single launch for dense surface coverage



GeNeSiS

Concept Advantages:

- Multiple, simultaneous bistatic measurements
- No transmitter - low cost, low power
- Constellations feasible (e.g. CyGNSS) - High spatial/temporal coverage
- Forward scattering, L-Band - Improved penetration through vegetation
- Increasing number of GNSS/SBAS transmitters - Currently ~120 transmitters
- Long-term GNSS stability



Decadal Survey Priorities Addressed:

- "Understanding the sources and sinks of carbon dioxide and methane, and how they may change in the future."
- "Quantifying trends in water storage…"

Decadal Survey Goals Addressed:

- Cost Effectiveness
- Science Continuity

Science

Wetlands: 177-284 Tg/yr
Fossil Fuels: 85-105 Tg/yr
Livestock: 87-94 Tg/yr

Primary Science: Wetland Inundation and Dynamics

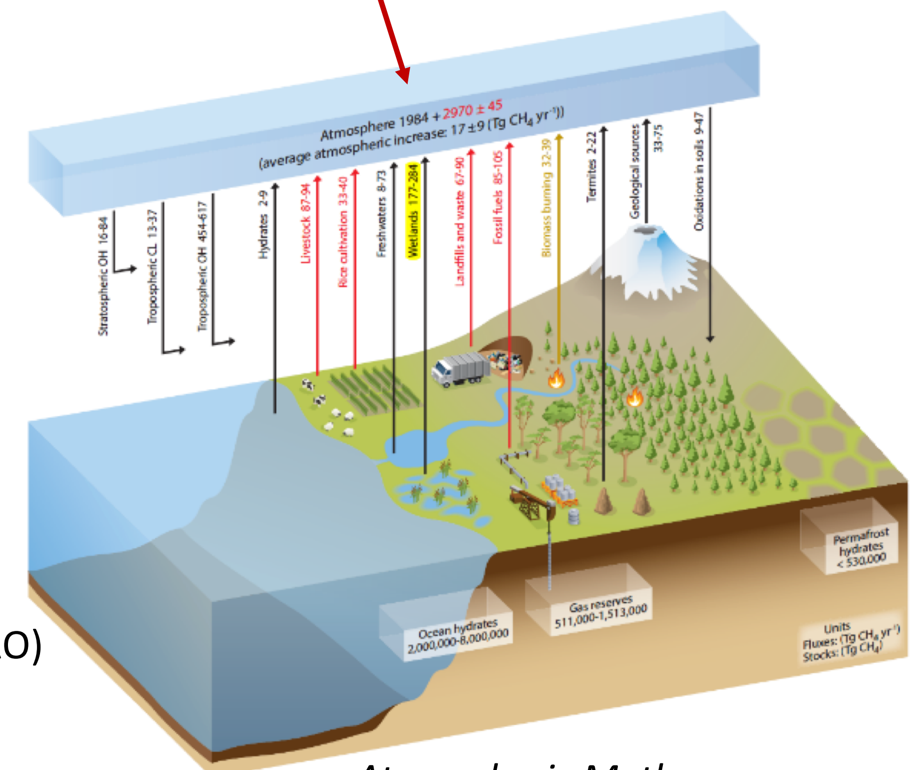
- Wetlands largest contributor to atmospheric methane
  - Largest contribution uncertainty
- Connections to carbon and water cycles
- Dynamics studies possible with high sampling rates

Secondary Science: Hydrology

- Soil Moisture
- Freeze/Thaw Cycle
- Heavy precipitation
- Sea-Ice Thickness and Melt Pond Fraction (polar orbit)

Other Capabilities:

- Polarimetric Radio Occultation measurements (GNSS-PRO)
  - Atmospheric temperature and humidity
  - Heavy precipitation
- Precise Orbit Determination (POD)



Atmospheric Methane
From IPCC AR5 Report

Science

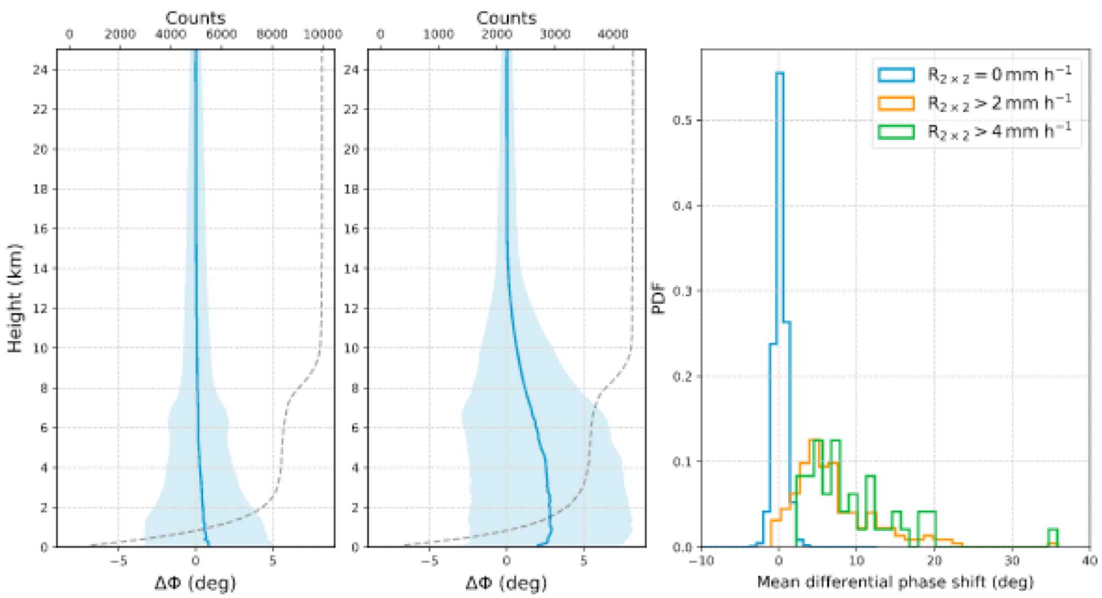


Figure 2. Mean and standard deviation of Radio Occultation and Heavy Precipitation aboard PAZ profiles at different altitudes (left) under rain-free conditions and (middle) under rain condition of any intensity. Upper axis and dashed line for the number of cases. See supporting information S1 for the geographical distribution of the rainy events. Right: Histograms of the individual profiles' $\langle \Delta\phi \rangle_{0--20km}$ under rain-free condition (blue, 9,959 profiles), $R_{2^\circ} > 2$ mm/hr (orange, 187 profiles) and $R_{2^\circ} > 4$ mm/hr (green, 43 profiles). More information on the extreme case with $\langle \Delta\phi \rangle_{0--20km} \sim 35^\circ$ shift can be found in supporting information S2.

"Sensing Heavy Precipitation with GNSS Polarimetric Radio Occultations", Cardellach, et al, GRL 2018

Recent Result:
Polarimetric Radio Occultations (GNSS-PRO) can sense heavy precipitation

Science Requirements

Wetland/Hydrology Science Requirements

Hydrologic cycle:

- Dynamics: runoff operates on ~4 week time scales

    Brakenridge, G. R., S. V. Nghiem, E. Anderson, and S. Chien (2005), Space-based measurement of river runoff, Eos Trans. AGU,86(19), 185–188, doi:10.1029/2005EO190001

- Catchment area / Wetland inundation extent: 1-2 km spatial resolution

    Nghiem, S. V., C. Zuffada, R. Shah, C. Chew, S. T. Lowe, A. J. Mannucci, E. Cardellach, G. R. Brakenridge, G. Geller, and A. Rosenqvist (2017), "Wetland monitoring with Global Navigation Satellite System reflectometry", Earth and Space Science, 4, 16–39, doi:10.1002/2016EA000194.

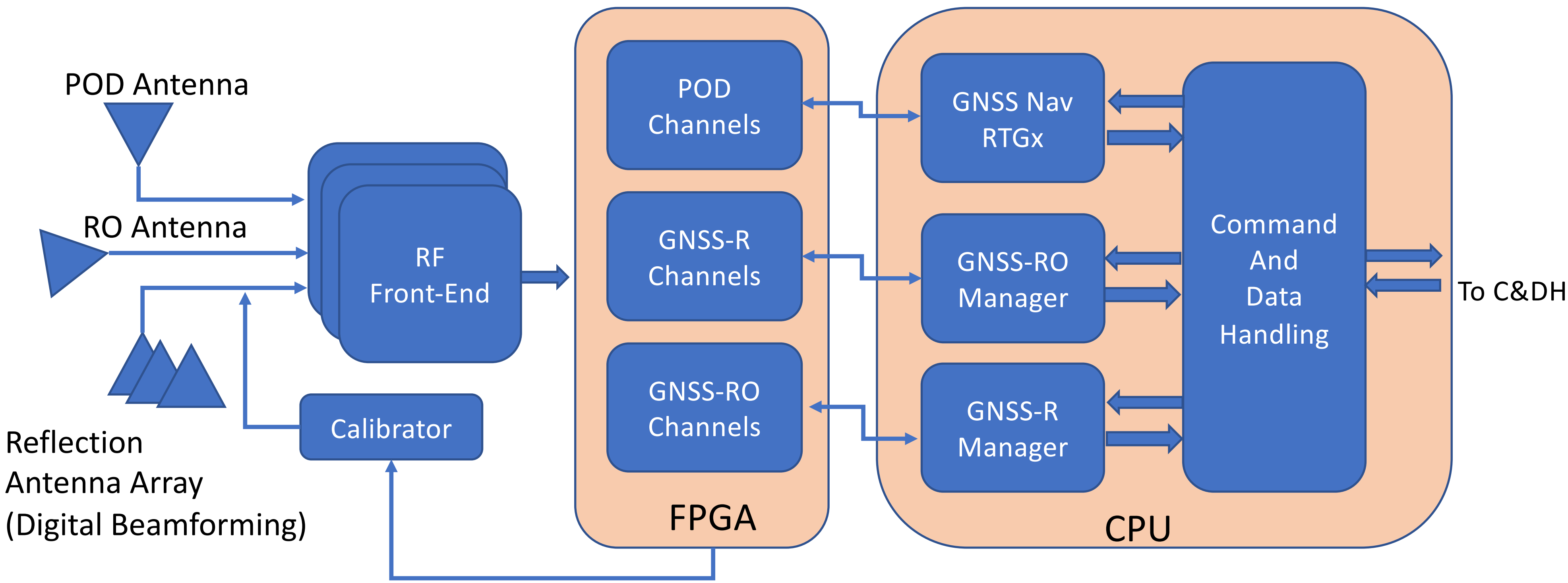
⟹ Require global (+/- 60º latitude) inundation maps every 2 weeks (Nyquist)

- Process all GNSS + SBAS signals
- 5 Hz observations: 0.5 km spot travels 1.5 km
- 2 km cell size: ⟹ ~2 receivers

Instrument Specifications

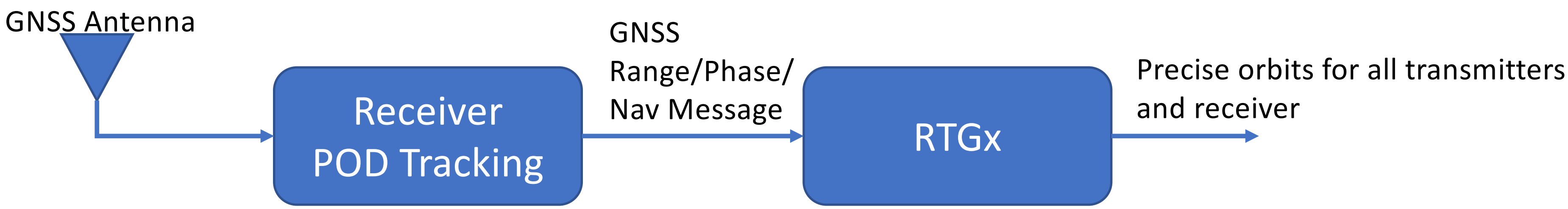
	Current State-of-the Art (Cygnss)	GENESIS	Motivation
Polarization	LCP	H/V or RCP/LCP (Dual Pol)	May help remove vegetation effects
Simultaneous Reflections	4	32	Improved coverage
GNSS Signals	GPS L1CA	2 signals from all GNSS	Improved coverage
Power	12 W	12-15 W	Small sat
Radiation	5 kRad	100 kRad	Good for all LEO orbits
Channel Bandwidth	4 MHz	40 MHz	Better delay precision
Radio Occultation Support	No	Yes	Additional science
Beamforming Support	No	Yes	Improved Coverage
Antenna Inputs	2	12	Improved coverage
Science Data Rate	1 Hz	10 Hz	Wetland cell size

GeNeSiS Block Diagram



GNSS Navigation: RTGx

- State-of-the-art GNSS navigation software package from JPL
  - **Gipsy**: holds POD records for GPS and LEOs – 100s of licenses to academia and industry
  - **RTG**: core SW for WAAS (U.S.), MSAS (Japan), GAGAN (India), core for GDGPS 2000-14
  - **RTGx:** for the Next Generation GPS Control Segment (OCX), developed for USAF
- Decimeter-level real-time on-board positioning
  - SW capable of cm-level performance - limited by ephemeris
- Orbit propagation (receiver, transmitter location at time t)
  - Input to model estimation for GNSS-RO, GNSS-R open-loop tracking



GNSS-R Processing: Delay Doppler Map

- Delay doppler map (DDM): matrix of received signal power vs. doppler and delay
- Primary observable for GNSS scatterometry
- Accumulation of incoming signal with signal model for various values of doppler and PN code delay

$$\text{DDM} = \int s(t)e^{j2\pi t(f_C+f_D)}\mathrm{c}(\mathrm{t}+\tau)dt,\ \forall f_D,\tau$$

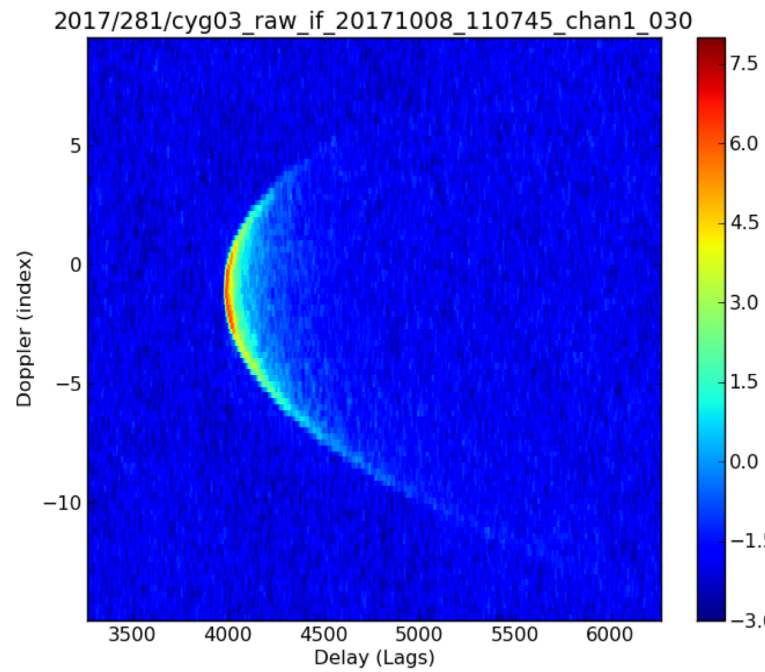
$s(t)$: *incoming signal*

$c(t)$: *PRN code sequence*

f_C : *signal carrier frequency*

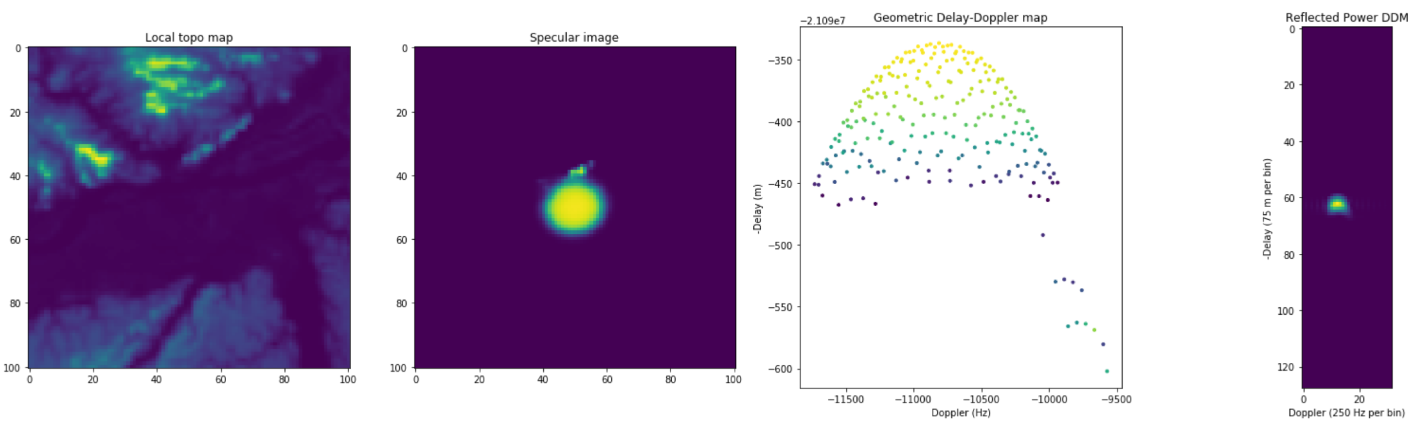
f_D : *doppler frequency (local signal model)*

τ : *code delay (local signal model)*



GNSS-R Processing: Specular Point Estimation

- Specular point estimation drives GNSS-R open-loop tracking model
  - Derives specular point location as a function time, receiver/transmitter location, topographic data
  - Determines delay/doppler of specular reflection (also az/el for beam steering)
  - Multiple levels of Earth surface modelling included:
    - WGS84 (ellipsoid)
    - EGM96 (geoid)
    - SRTM (topography)

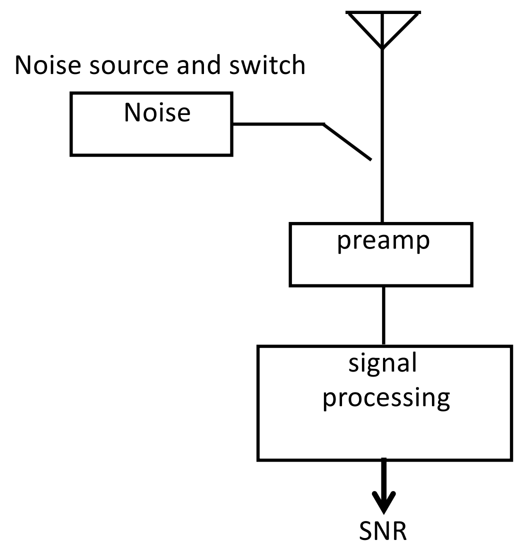


GNSS-R Processing: Calibration

- **Motivation: Turn DDM into normalized bistatic radar cross section (NBRCS)**

System noise calibration approach:

- Inject known noise source (N) into signal path with synchronized switch
  - *Young L. et al, "Method to measure total temperature of a wireless receiver during operation", US Patent: 8,688,065 B2, 2014*
  - Measure SNR with added noise
  - Measure SNR without added noise
  - Solve for system noise (T_{sys}) with these measurements
  - Perform this continuously, no interruption to data collection



Advantages:

- Accurate measurement of T_{sys}
- Continuous calibration with minimal degradation of primary measurement
  - 0.5 dB loss for 10% noise duty cycle
- Simple hardware configuration (noise source + RF switch)

GeNeSiS Deliverables

- Engineering Model Receiver Hardware (TRL6)
  - Tested for function/performance over temperature
  - Calibration noise source included
  - Antenna not included
- Complete GNSS-R Software Package
  - Multi-frequency support
  - Multi-GNSS support
- Receiver Calibration Algorithm
- Flight Tests (Armstrong Kingair aircraft)
  - EM hardware + software + COTS antenna
  - Instrument operated over relevant terrain

Summary

- **We're building a highly capable GNSS reflectometry instrument for space applications**
  - Improved number of simultaneous DDMs
  - Improved number/type of GNSS signals processed
  - Improved number of antenna inputs

- **Unique features:**
  - Antenna arraying for improved SNR and coverage
  - RTGx for Position, Navigation and Timing (PNT)
  - Continuous noise calibration system (no deadtime)
  - Polarimetric radio-occultations (GNSS-PRO) for heavy precipitation